Actuators

→ **Why have moving parts in the accelerator??**

We will already have "moving parts" due to ground motion.

Physical magnet adjustments could reduce the burden on correctors, particularly in the low field design context.

Zero power high order correctors for low field magnets can also be realized.

<u>Other candidate systems for low speed actuators:</u>

Collimators
Cryo valves
Multiwires
Lambertson positioners

<u>Actuator technology options:</u>

Steppers, Servos

> **Common, mature technologies**
> **Cost ~$200-300 each (quantity cost?)**
> **Requires regulated DC supply and controller**

Would like to find a "motor" which:

> **Is inexpensive, simple, and reliable**
> **Is not picky about its power source**

A potential technology presents itself, but

R&D

is needed…

A concept for an inexpensive low speed rotary actuator utilizing Shape Memory Alloy filaments

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Several technologies may be considered for use in remote actuation mechanisms, such as the familiar stepper motor, and AC and DC servomotors to name a few. A relatively new technology, which has seen increasing use in aerospace and medical applications, is based on shape memory alloys, or SMAs. These materials, typically alloys of Titanium and Nickel, deform easily at low temperatures but undergo a solid state thermoelastic phase change at elevated temperatures, returning to their original shape and potentially delivering significant work in the process. One form of this material, Flexinol wire (mfd. by Dynalloy Corp[i]), has been processed to produce a longitudinal contraction of about 5% when heated electrically and can be cycled tens of millions of times. It is suggested that this material may be used to construct low speed remote actuators suitable for accelerator applications.

The SMA wire filaments are currently available in several diameters ranging from 1 to 15 mils. The factors governing the choice of size are desired contractile force, heating/cooling rate, and electrical resistance. For example, 10 mil Flexinol wire filaments have the following specifications:

Contractile force: 2 lbs.
Transition temp: 70C or 90C
Resistance: 0.5 ohms/inch
Heating current: 1 Amp
Heating time: 1 second
Cooling time: 5.5 or 3.5 s (depending on trans. temp)
Cost: $3.60/meter in quantity

In order to convert the longitudinal contractions to rotary motion (to drive a screw jack, for instance) it is proposed to use a windlass mechanism. An example "thermoelastic motor" illustrating this configuration is pictured in figure 1. Two 10 mil SMA filaments are wound onto a four inch diameter electrically nonconductive drum such that their contraction tends to rotate the drum in opposite directions. The filaments are each anchored to a stationary reaction block, passed once around the drum to an attachment pin, then back in the opposite direction to the block again. Five such passes yield ten strands, which are mechanically in parallel and electrically in series. Two filaments so attached thus pull against each other, rotating the drum back and forth as the heated filament contracts and the cold filament stretches. The hub of the drum contains a ratchet mechanism which "rectifies" the rotary oscillations into pulsed unidirectional output shaft rotation. Another pair of short SMA filaments attached to the ratchet pawl allows the direction of shaft rotation to be set by momentarily heating one or the other filament. The force required to stretch a cold filament is approximately 17% of the force exerted by a heated filament, so the total available excess tangential force is 265 oz, neglecting frictional losses on the drum. A maximum torque of 531 oz-in is then available at the output shaft (again neglecting drum friction), a value comparable to a large stepper motor.

The rotation speed is dependent on the thermal time constant of the filaments, which is strongly dependent on the surrounding environment. Using the manufacturer's numbers for free air and overlapping the 3.5 second cooling time with the 1 second heating time of the opposing filament, we get approximately a seven second period between successive contractions of a given filament. Each contraction in the engaged direction of the ratchet gives 18 degrees rotation, so a complete rotation of the output shaft takes 20 complete thermal cycles, or 140 seconds. This rate will no doubt be significantly altered depending on the thermal characteristics of the drum. A thermally insulating drum would lengthen the cooling time but may shorten the heating time. A thermally conducting drum would shorten the cooling time at the probable expense of a higher required heating current. Figure 2 shows a drum featuring a fluted surface to minimize the thermal contact area with the filaments, more closely approximating the free air condition of the manufacturer's specifications. Clearly the configuration and composition of the drum are most critical to the performance of the actuator, requiring careful consideration of frictional and thermal characteristics.

Another topic to consider when evaluating actuator technologies is the complexity of the required support circuitry. The thermoelastic motor, being a thermal rather than magnetic device, does not require a regulated power supply when used in a binary, as opposed to proportional, mode. Consider the example device in figure 1 with a voltage requirement of 60V. The required power could in fact be obtained directly from the 120 volt AC mains with an SCR providing half-wave rectification, resulting in an easily gated 60VRMS drive signal. Figure 3 illustrates a possible configuration of the actuator circuitry using steering diodes on both the torque and direction filaments. This reduces the power cable conductor count to three wires and neatly interfaces with a power supply consisting of only four small SCRs fed from a single phase 120 volt line. Unlike most motor power supplies, no voltage regulation or filtering circuitry is needed.

Figure 4 shows a typical sequence of power applied to each filament. The motion cycle begins by initializing the ratchet pawl with a pulse to the appropriate direction filament, after which the drive sequence commences. Each heating pulse is approximately one second long followed by a cooling period before the opposing filament is heated. The direction of rotation can be reversed by pulsing the other direction filament during any cooling interval of the torque filaments. The lower two traces show the corresponding half-wave AC outputs from the SCR power supply of figure 3.

In figure 5, the example actuator is shown driving a worm gear reducer and screw jack. In this configuration it directly replaces a stepper motor. Also illustrated is the ventilated housing, which allows reasonable filament cooling rates. One disadvantage of the vents is that the actuator mechanism is susceptible to dust and contamination.

Figure 6 shows an alternative means for removing heat from the device. The outer casing is formed from a cylindrical aluminum extrusion having internal and external fins to promote heat transfer to the surrounding air while maintaining a sealed internal environment. Under extreme cycling requirements, this design could conceivably be oil-filled to provide even higher cooling rates.

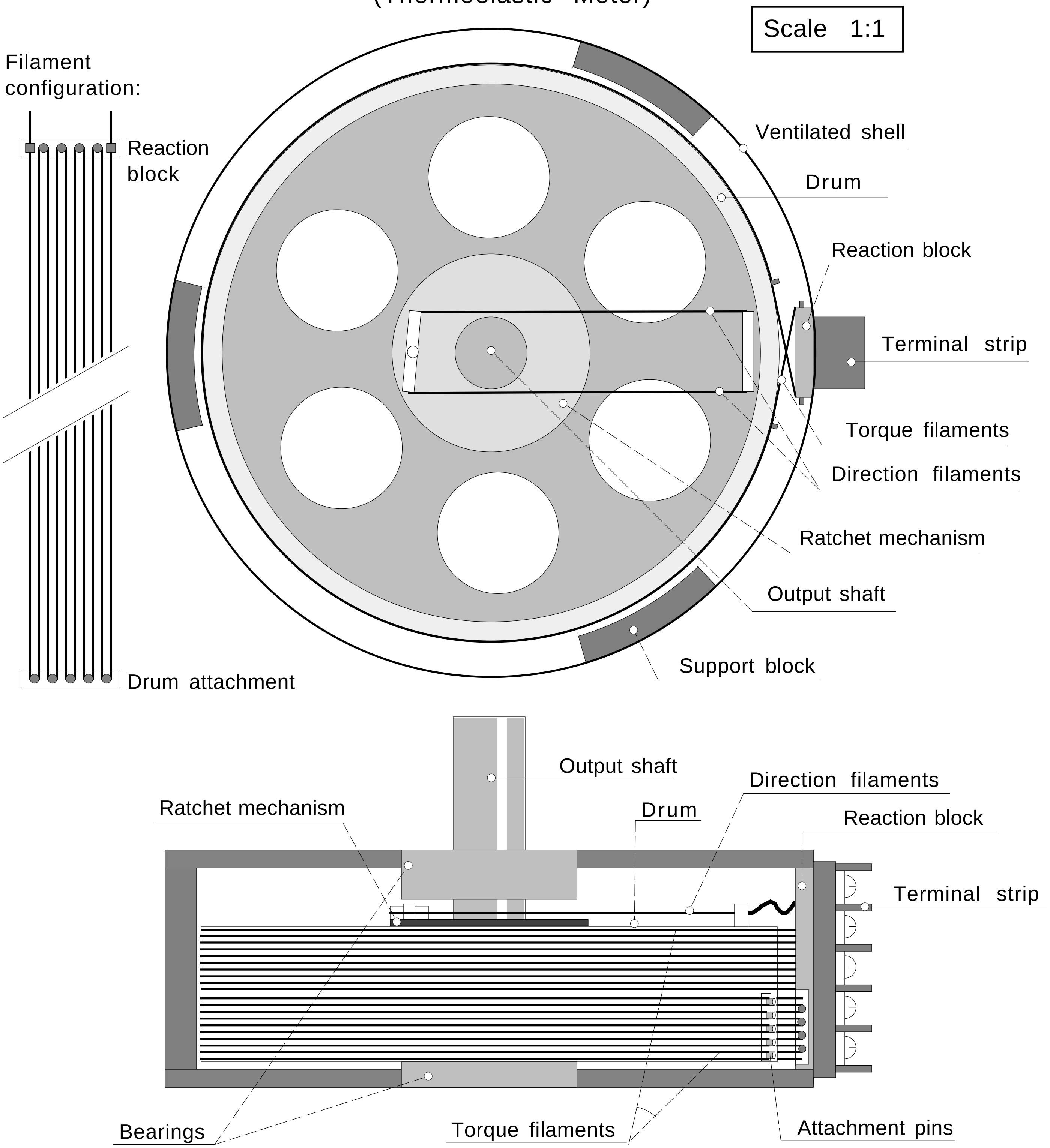
Figure 7 illustrates a high resolution linear output version of the actuator. This configuration features an internal arrangement which makes use of the otherwise largely wasted space inside the drum. Here a ratchet pawl attached to the inside wall of the drum engages a gear train which drives an internal screw jack. Since the drum only rotates 18 degrees, its spokes do not interfere with the two gear hubs passing through its base. This internal gearing method could also simply provide a high resolution, high torque rotary output.

Conveniently, the aspect ratio of the drum may be altered to suit the physical mounting requirements of the device without changing the output torque if the total filament lengths remain the same. Figure 8 shows a two inch diameter drum which is twice as long as the example of figure 1. Here the filaments undergo 20 passes each, doubling the tangential force and compensating exactly for the 50% smaller radius.

This basic concept can of course be applied to other mechanical configurations to no doubt realize better performance for specific tasks. Linear “inchworm” drives may be constructed using SMA filaments for appropriate applications. Fully proportional control using SMA filaments has been shown to be possible and may allow small high precision positioners to be constructed without the need for gearing to increase resolution. Unfortunately no commercial versions of these devices yet exist, so evaluation of the performance of this technology will require prototypes to be built, tested, and optimized.

[1] Dynalloy Inc. 3194 Airport Loop Dr. Costa Mesa Ca. 92626-3405
www.dynalloy.com

Figure 1: Shape Memory Alloy Rotary Actuator
(Thermoelastic Motor)



Stroke: 18 degrees
Rate: ~140 sec/rev
Torque: ~500 oz-in
Current: 1 A @~60V
Average power: 24W

SMA filament length: 6.5 meters
Filament diameter: 10 mils

Approximate SMA wire cost: $23/unit

Figure 2: Fluted drum surface to minimize filament contact area

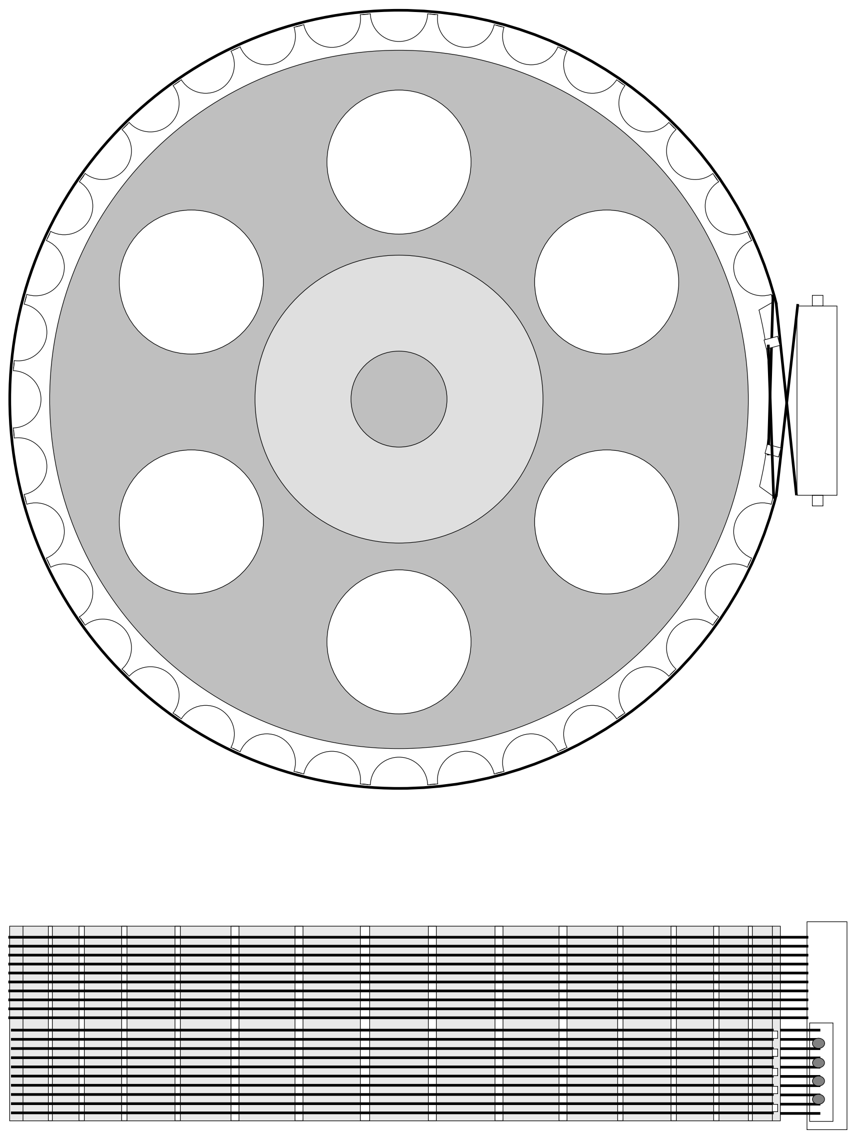


Figure 3: Electrical configuration of actuator and AC power supply

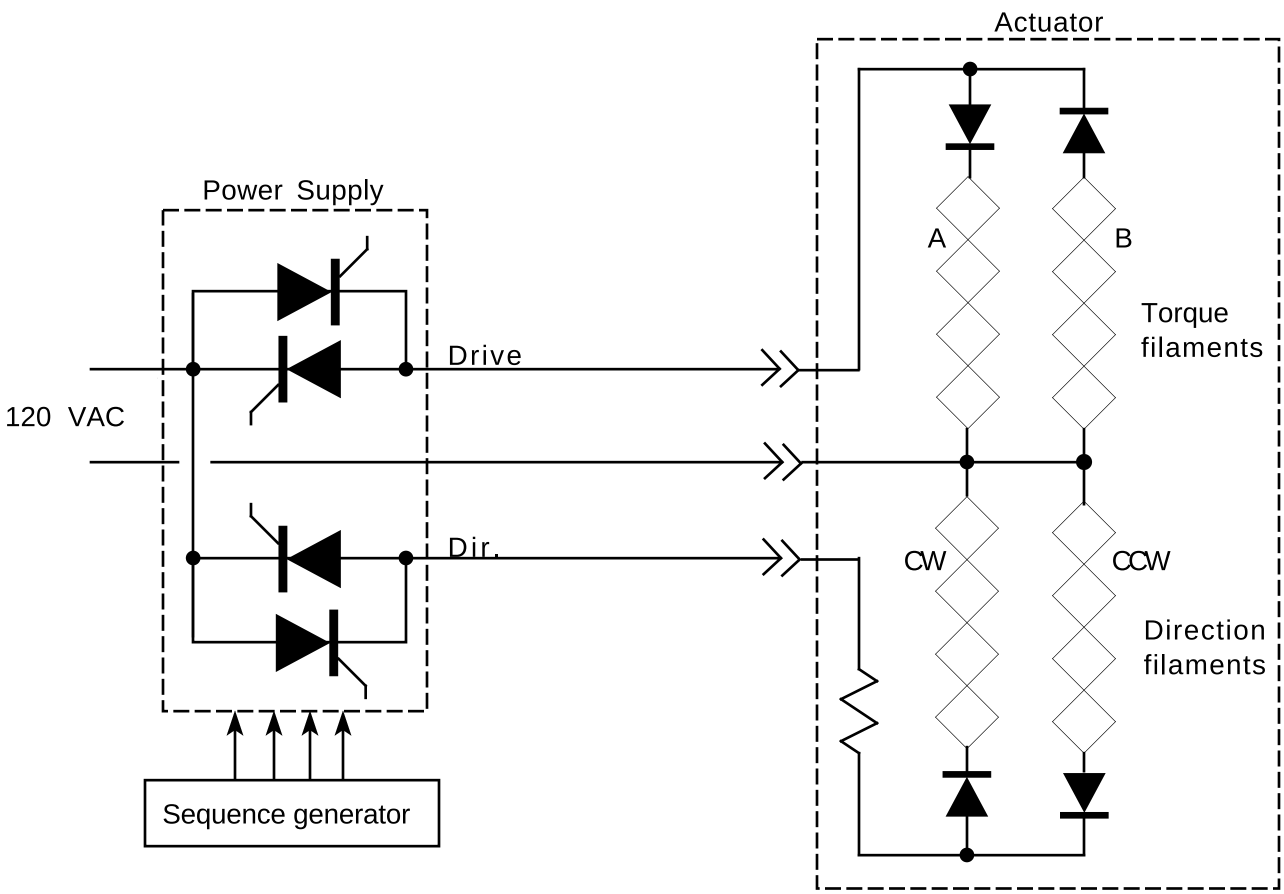


Figure 4: Actuator control sequence

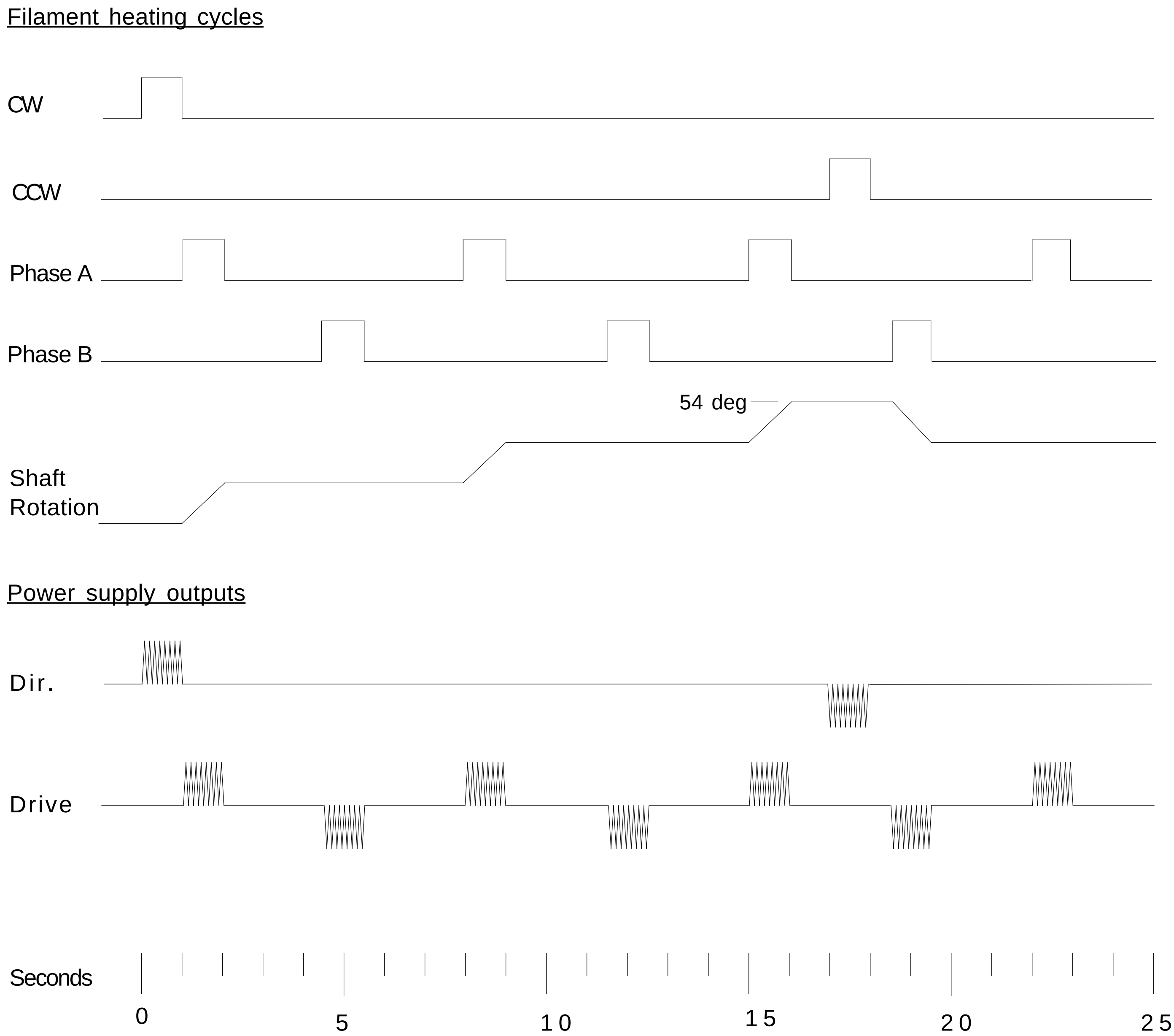


Figure 5: Actuator driving worm gear reducer and screw jack

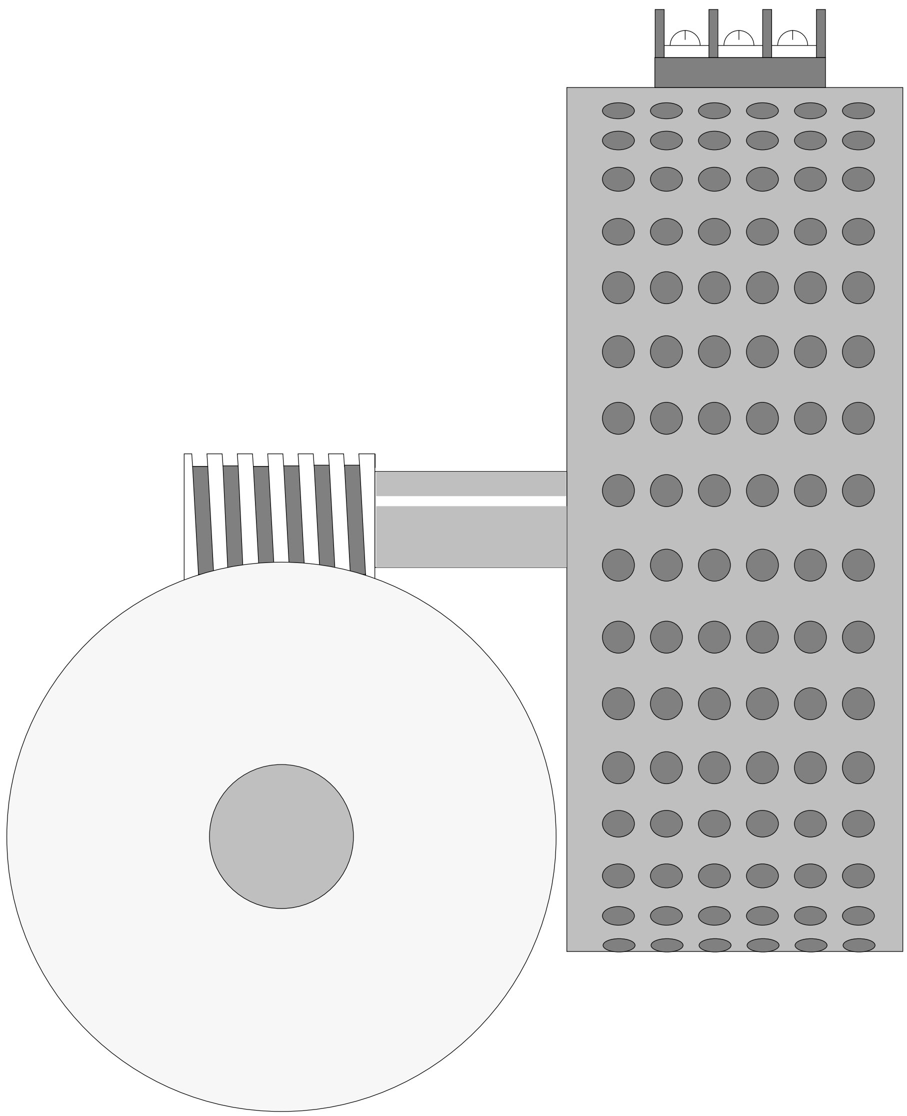


Figure 6: Extruded aluminum housing for improved heat transfer

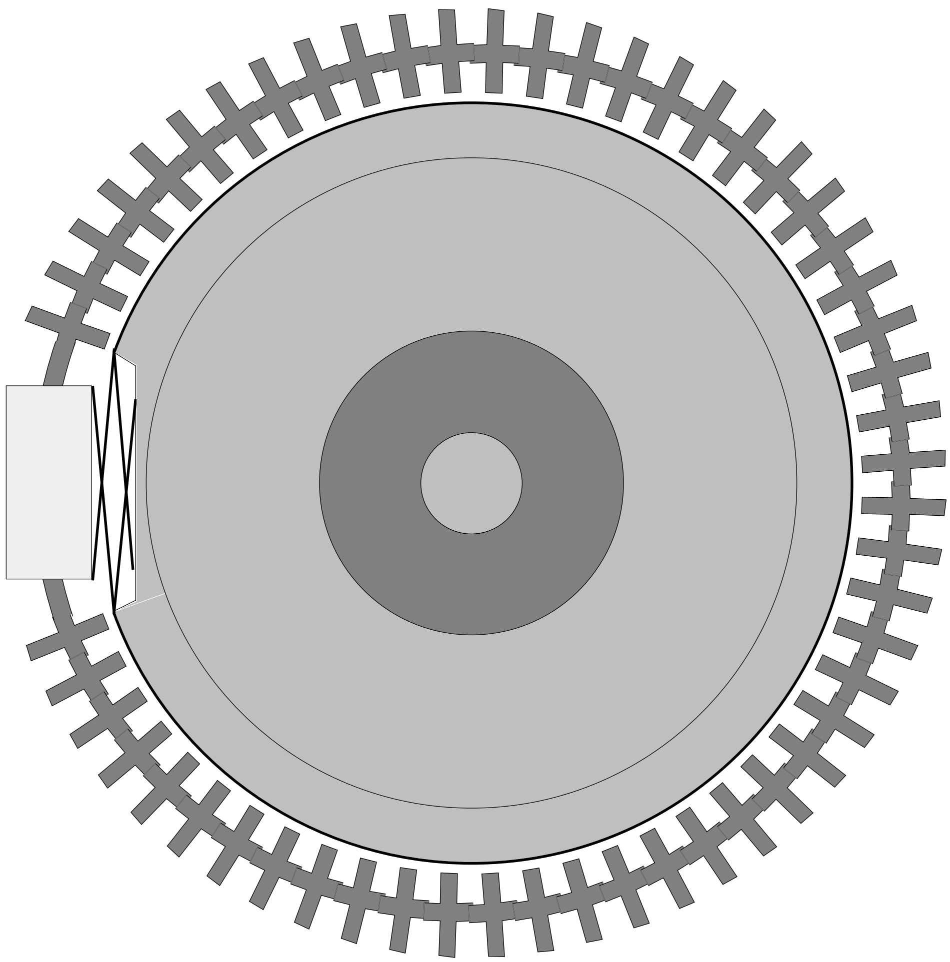
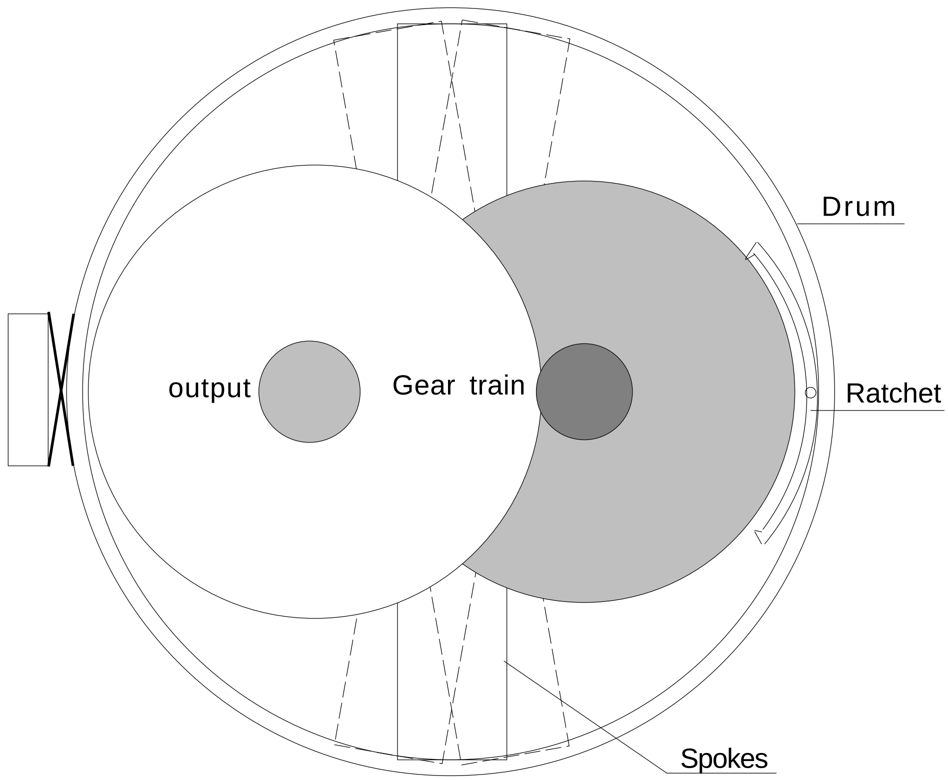


Figure 7: Actuator drum with internal gear reducer



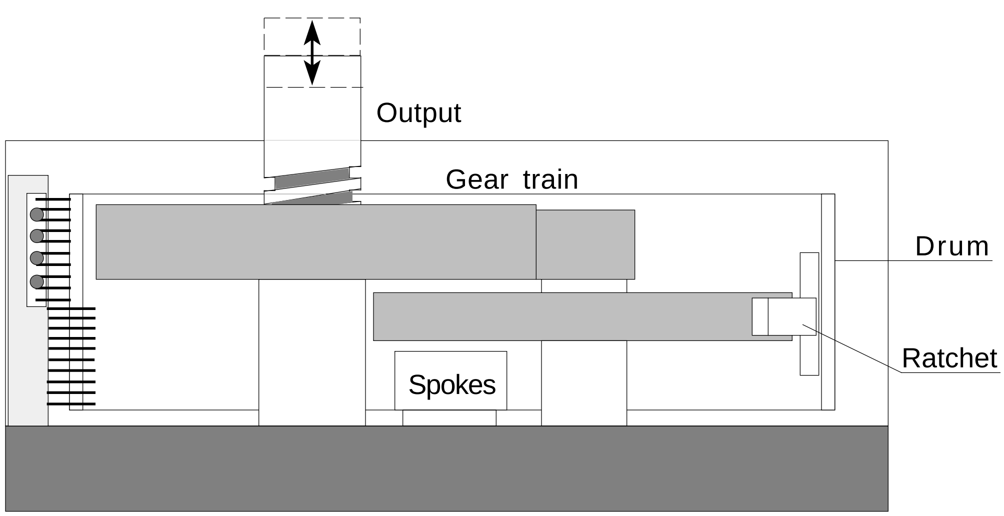


Figure 8: Smaller diameter drum with same torque output